Lithosphere asthenosphere boundary

Current state of knowledge

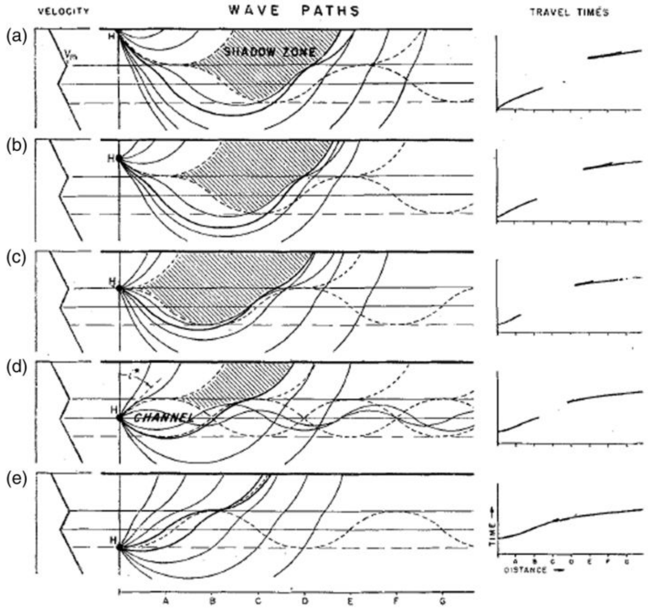
History of the Lithosphere-Asthenosphere Boundary

- The terms “lithosphere” and “asthenosphere” were first coined by Barrel (1914) to explain surface topography

- First evidence for the asthenosphere came from observations of low velocity “shadow zone”, interpreted as the asthenosphere low velocity zone (LVZ)

- Continued investigation of the LVZ from body wave arrival times indicate LAB depth varied with tectonic environment and continental or oceanic lithosphere

- Following the theory of plate tectonics, for a time the LAB was determined by half-space cooling models

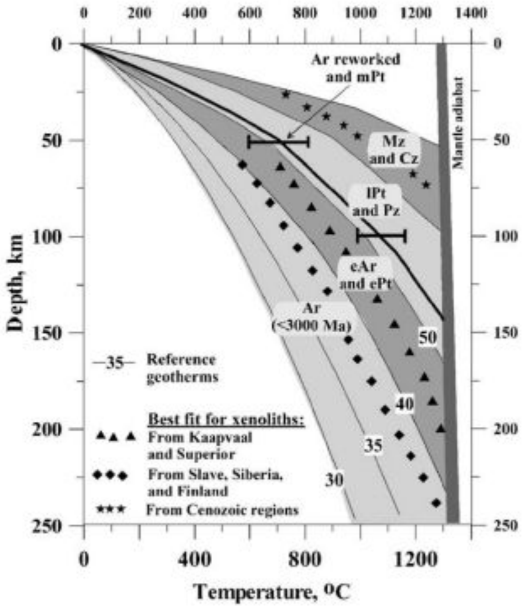


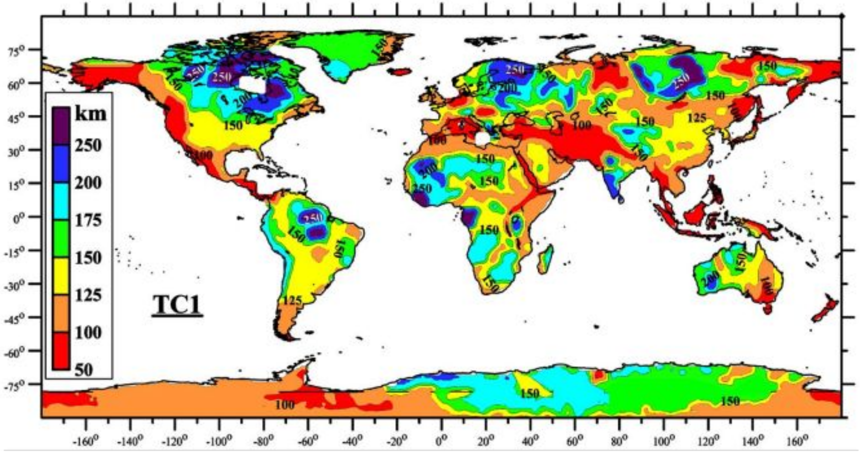
The shadow zone with EQ depth (Gutenberg, 1948)

Thermal models of the lithosphere-asthenosphere boundary

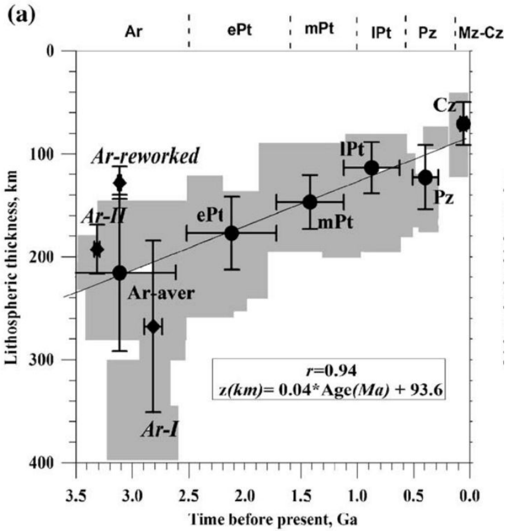
Thermal models estimate the depth of the lithosphere-asthenosphere boundary based on the 1300C isotherm, below which mantle rocks behave rigidly and transfer heat via conduction.

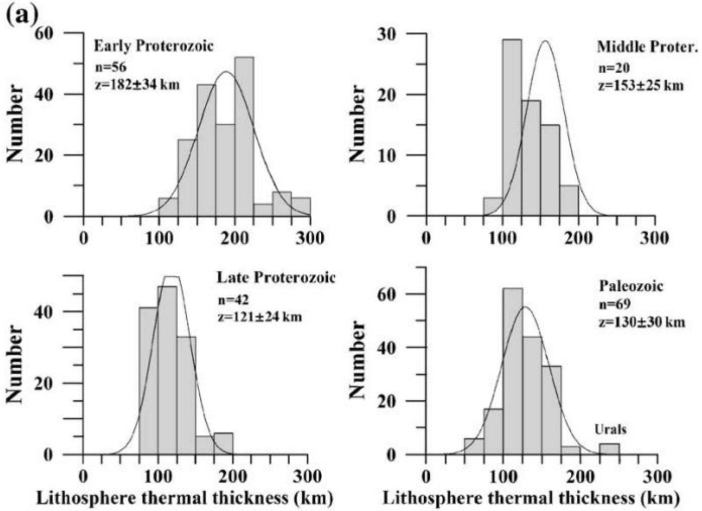
The thermal boundary exits point where geotherms intercept with the mantle adiabat of 1300C.





Artemieva (2006) produced a thermal model for the continental lithosphere based on heat flow measurements constrained by xenolith data.





Strong statistical relationship between tectonic age and the depth of the LAB.

Temperature is a dominant control on lithosphere thickness!

¨However, for a given age there is a large variability in LAB depths by 150 km.

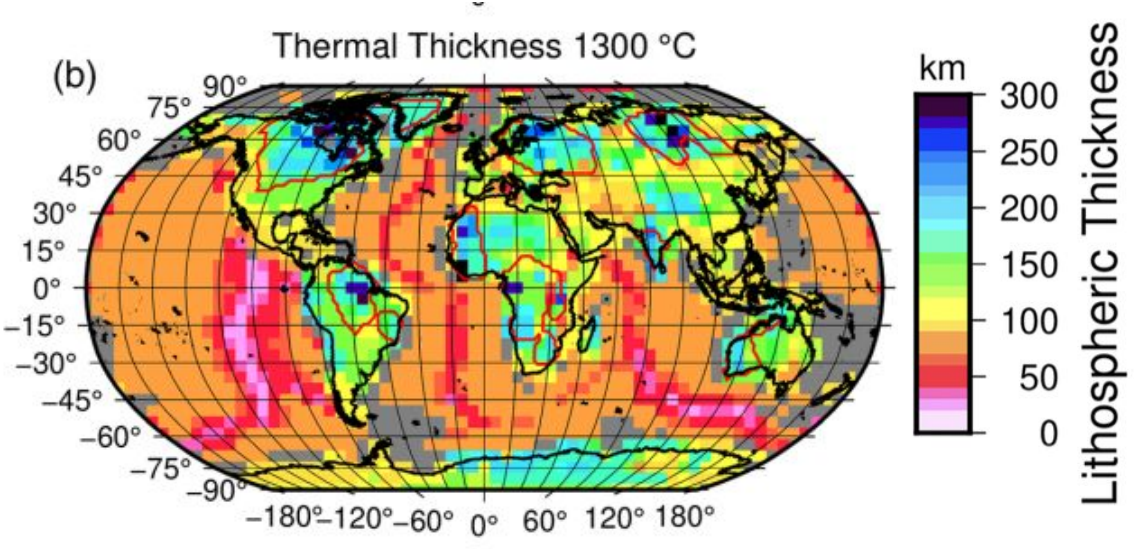
Other processes must be controlling the thickness of the lithosphere

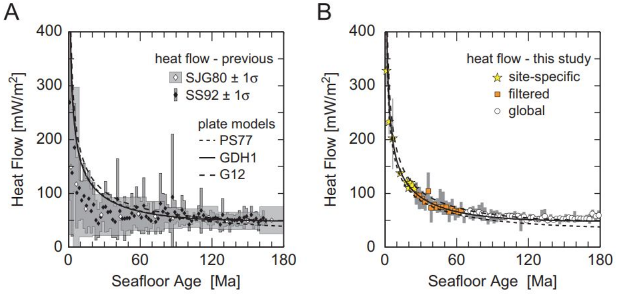
Important characteristic: In the thermal model, there is a gradual transition from the lithosphere to asthenosphere over tens of kilometres

Thermal thickness for oceanic crust

Predictions on the depth of the LAB for oceanic crust relies on ocean cooling models constrained by heat flow measurements.

These models are perturbed by hydrothermal circulation of younger oceanic crust (<50 Ma) and they avoid heat flow measurements for young oceanic crust.



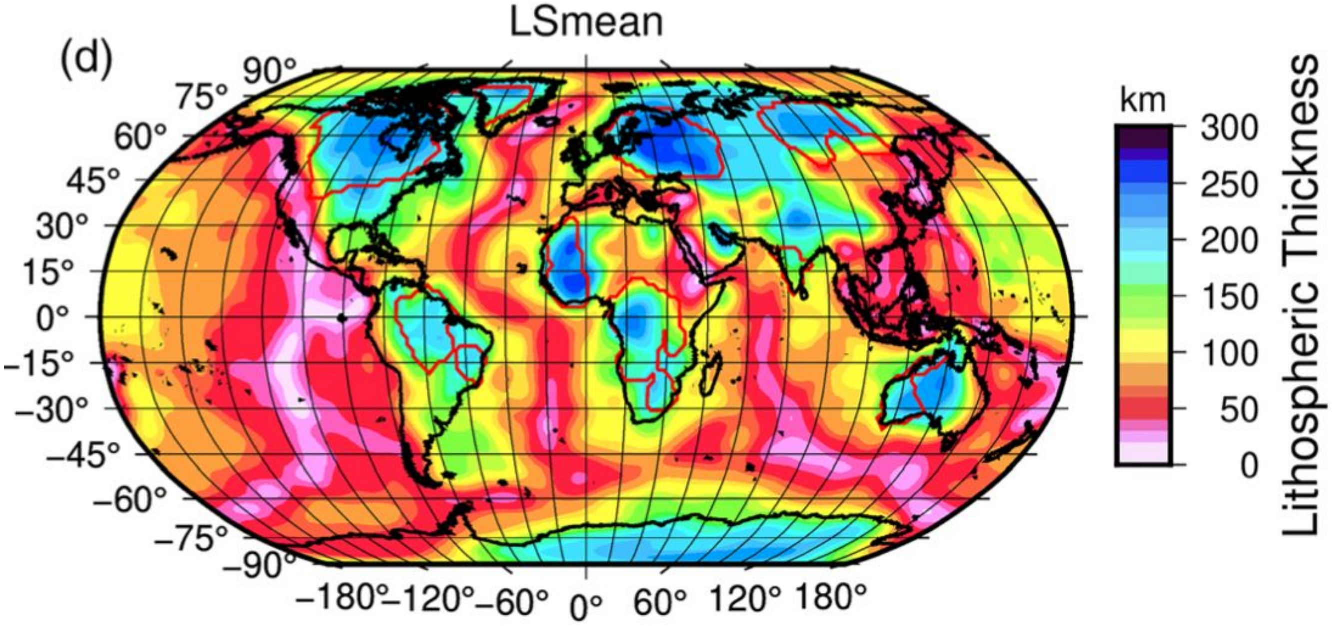


Hasterok (2013) developed new ocean cooling model that filters out the hydrothermal effect.

Improved correlation with heat flow measurements estimates a shallower lithosphere-asthenosphere boundary than previously estimated (90 km)

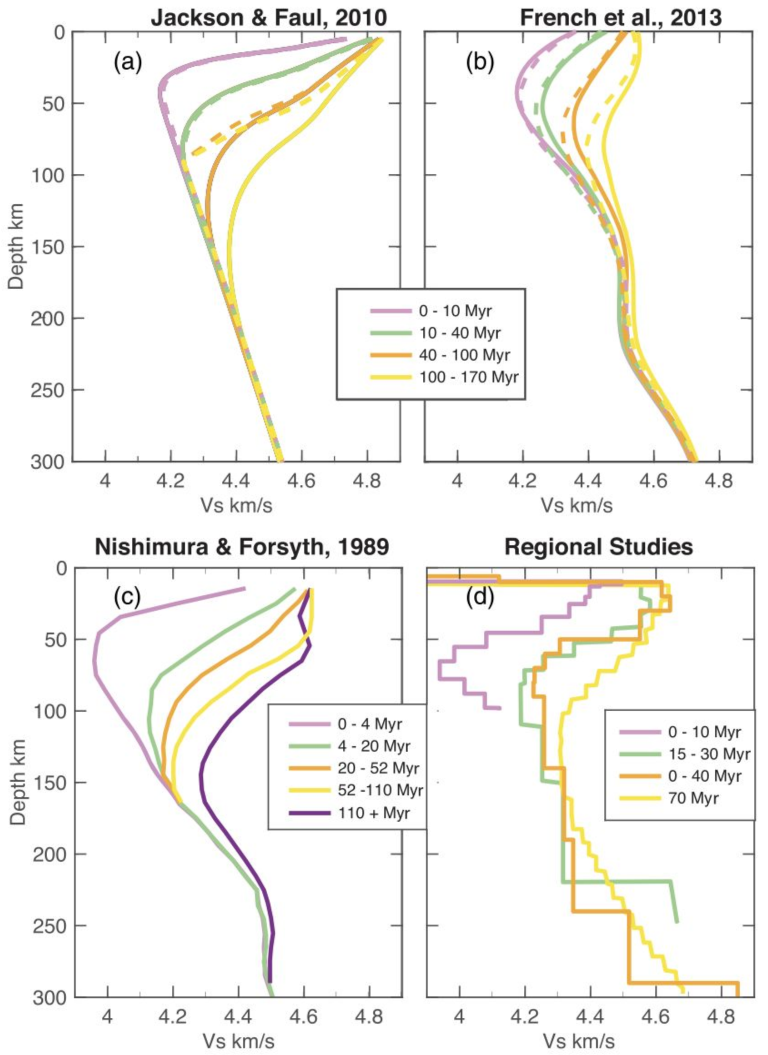
Recent seismic observations - isotropic

- Surface wave tomography
- Scattered waves
- Active source seismic reflection



Recent seismic observations - isotro

- Surface wave tomography
  - Difficulty of getting an exact thickness
    - <u>The exact shape of shear wave velocity-depth profiles differs</u>
    - <u>Surface waves have broad depth sensitivity kernels resulting in gradual velocity drops in depth</u>
    - The age-averaged profiles result in smooth, monotonic variations with age as predicted by thermal models, individual transects show greater variability



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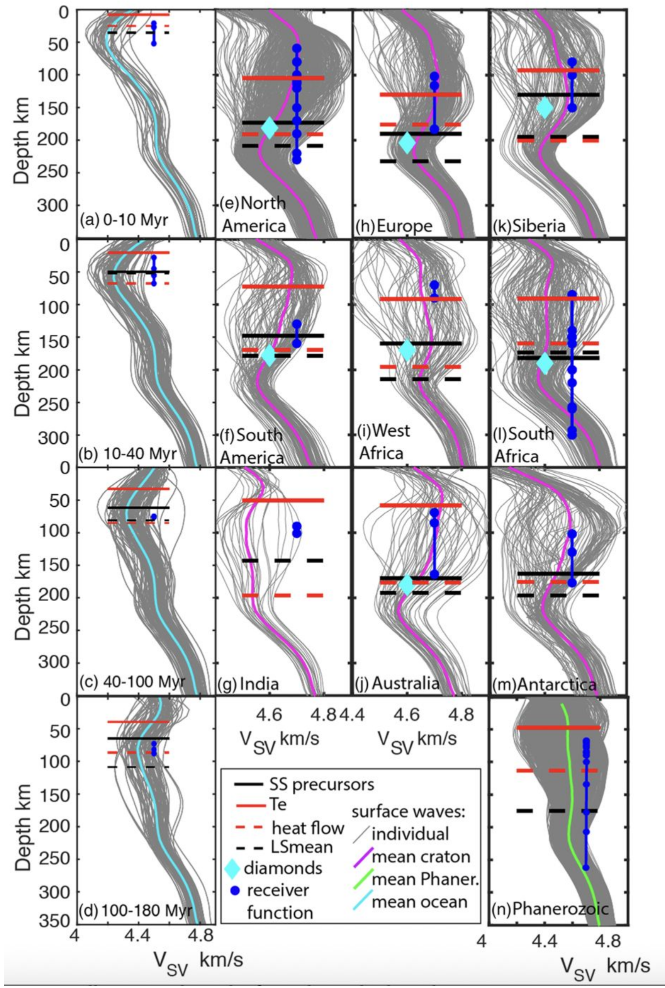

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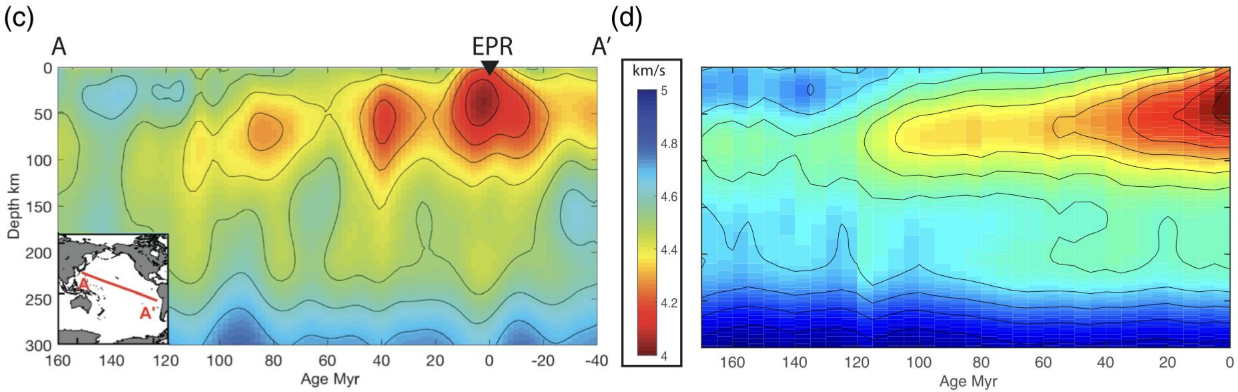

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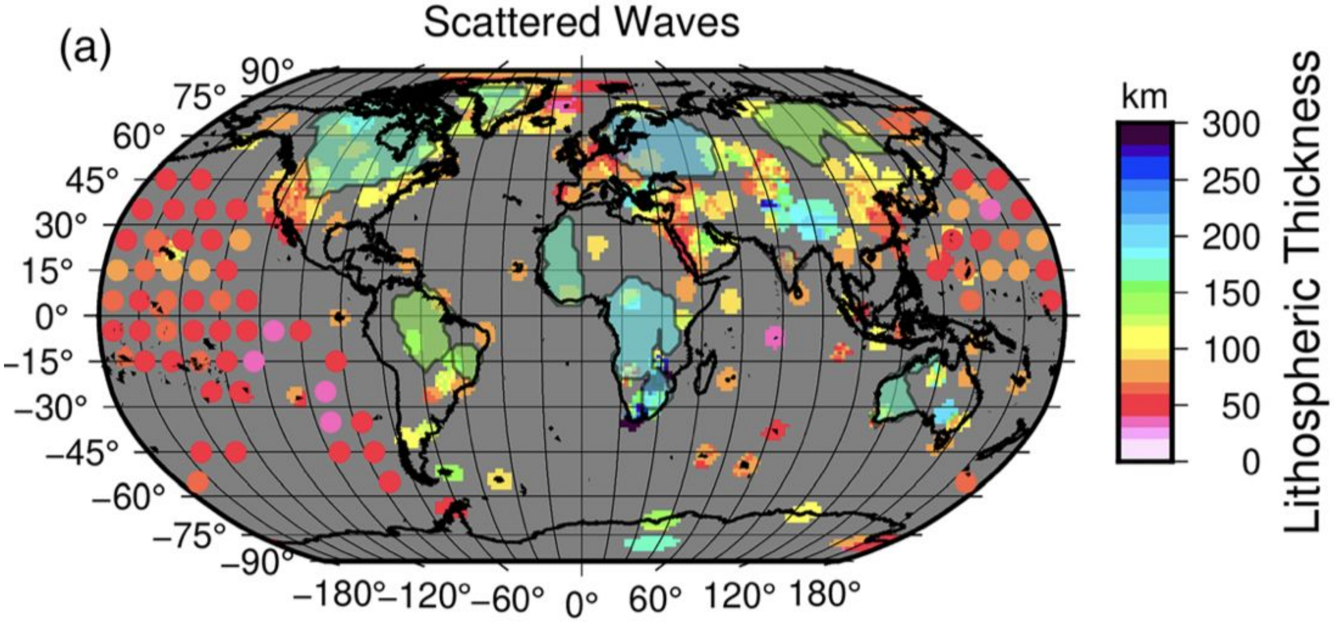

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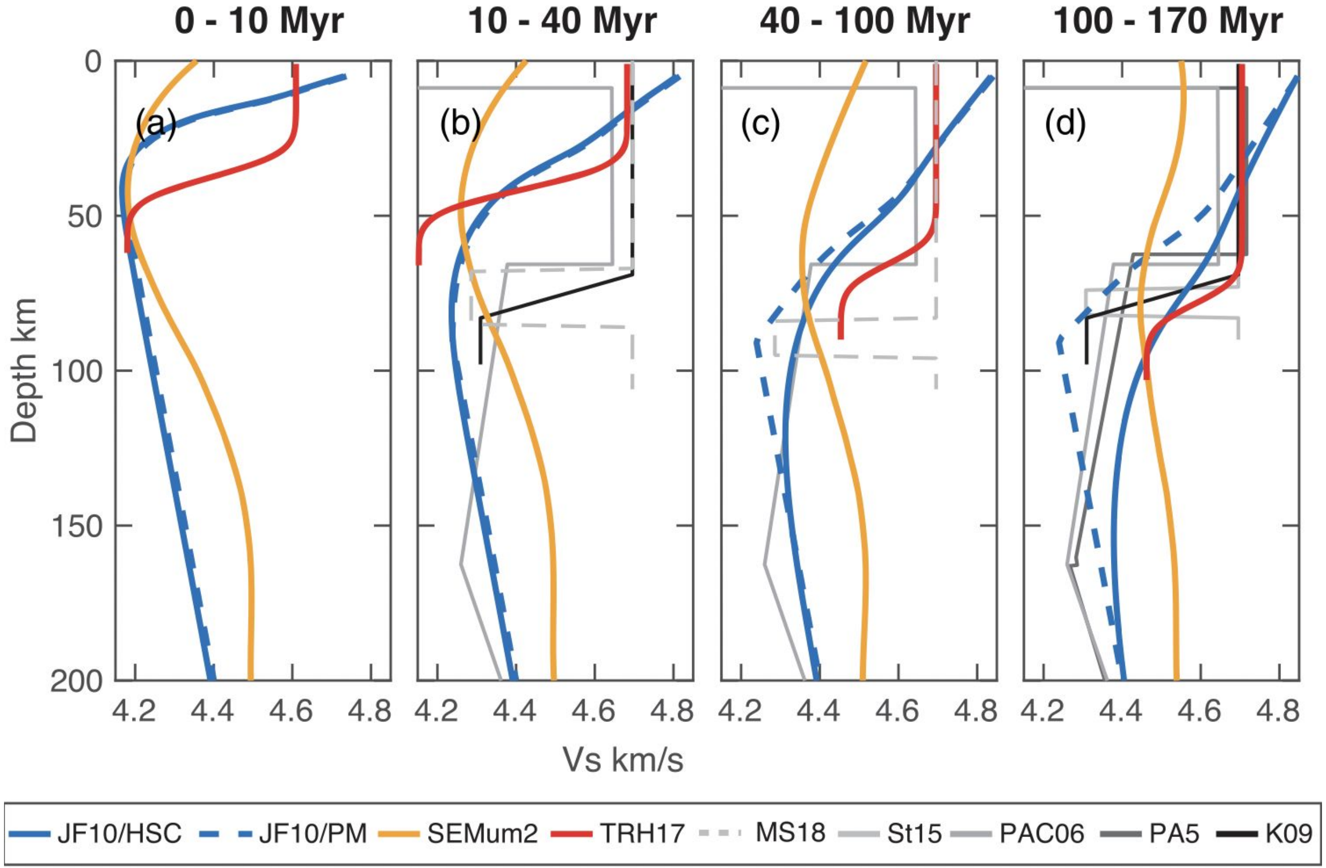
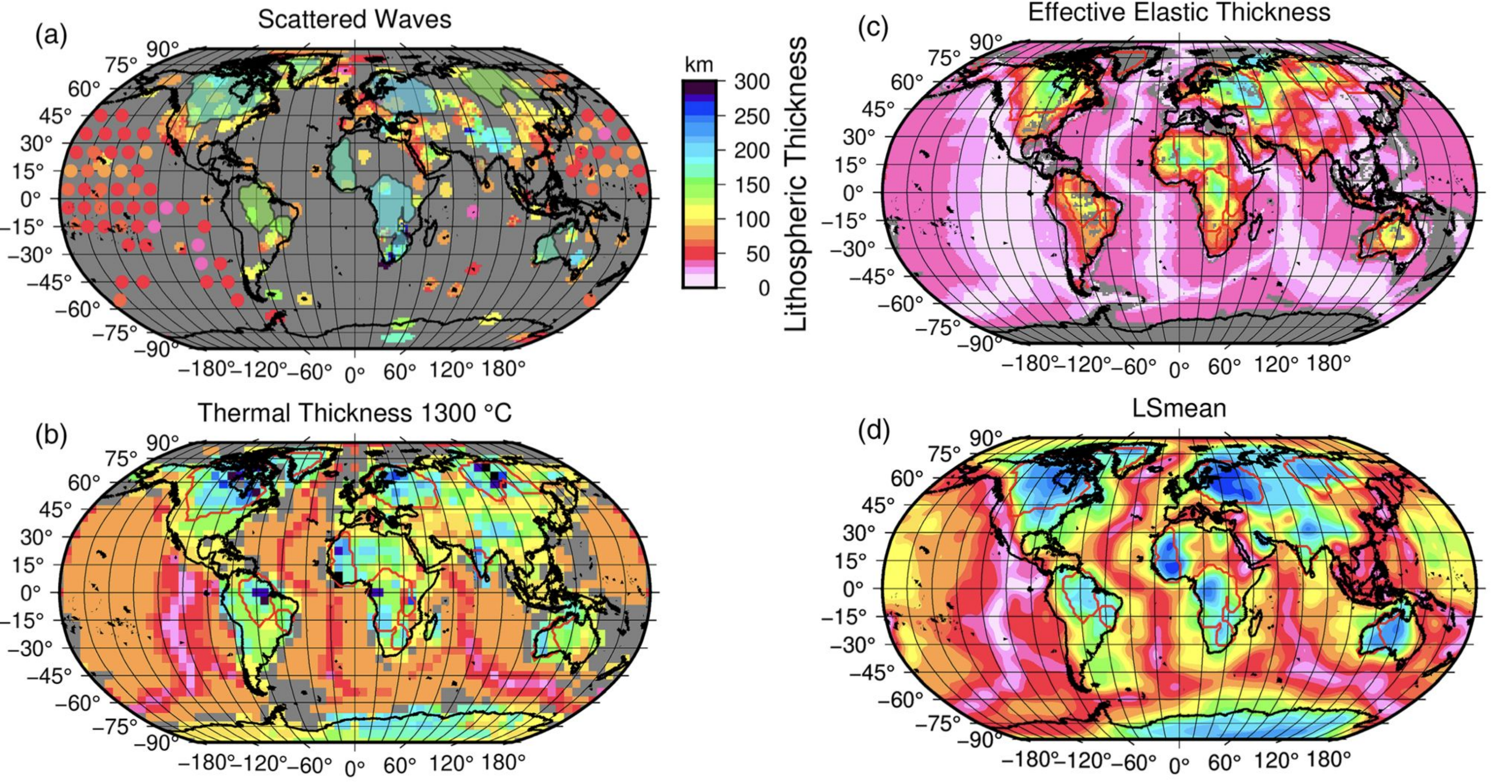


Recent seismic observations - anisotropic

- Seismic anisotropy
- LAB as the transition with depth from one fast direction to another
- Generally, this transition gets deeper with age (Maggi et al., 2006)
- Challenges
  - depth constraints coming from surface wave observations
  - fast-axis might not be aligned with APM in the asthenosphere
  - regional studies do not necessarily support simple fossil spreading orientations in the sub-crustal lithosphere
- Future
  - Need to simulate anisotropic fabric development under different deformation mechanism
  - Need more observational constraints for anisotropy
- Can be sharp with a shear zone but no tight observational constraint

Comparison

- Overall agreement that lithosphere thickens with age shows that temperature dictates the thickness of lithosphere to first-order
- Oceanic lithosphere
  - General agreement between surface wave and scattered wave depths - sharp
  - Variabilities in depths from different studies and methods
- Continental lithosphere
  - Average or individual
  - Sharp discontinuity?
  - Influence of complex structures



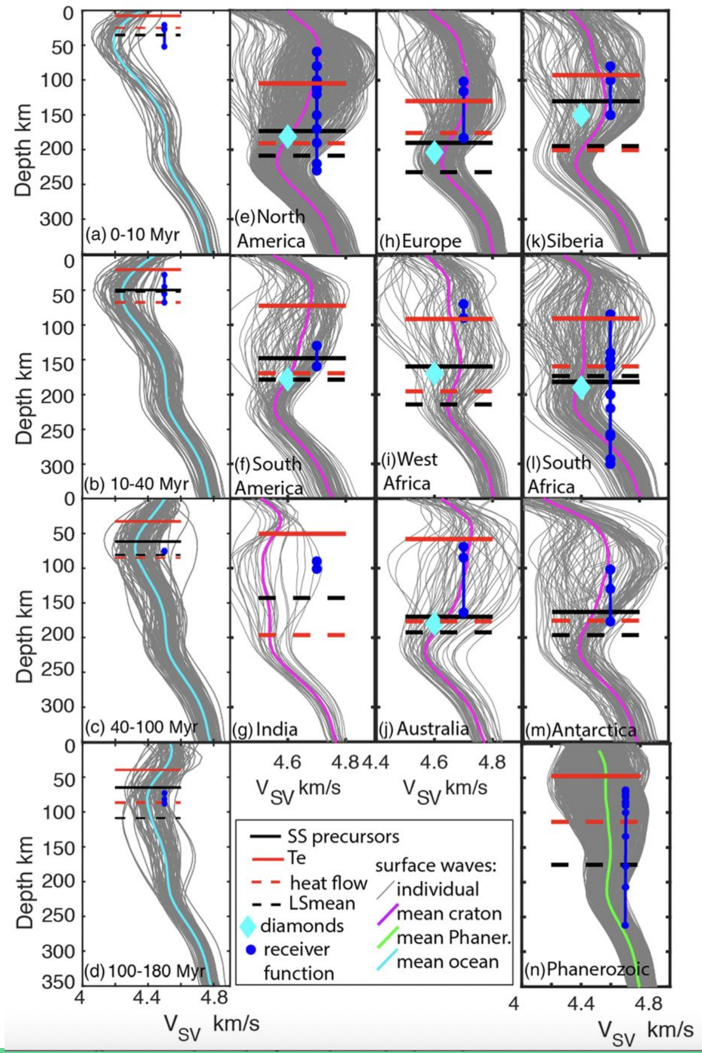
(a)
Scattered Waves
(b)
Thermal Thickness 1300 °C
(c)
Effective Elastic Thickness
(d)
LSmean
km
300
250
200
150
100
50
0
Lithospheric Thickness
90°
75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
−90°
−180°
−120°
−60°
0°
60°
120°
180°

Comparison

- Overall agreement that lithosphere thickens with age shows that temperature dictates the thickness of lithosphere to first-order
- <u>Oceanic lithosphere - near the 1100 C isotherm</u>
  - General agreement between surface wave and scattered wave depths - sharp
  - Variabilities in depths from different studies and methods
- Continental lithosphere
  - Average or individual
  - Sharp discontinuity?
  - Influence of complex structures

Comparison

- Overall agreement that lithosphere thickens with age shows that temperature dictates the thickness of lithosphere to first-order
- Oceanic lithosphere
  - General agreement between surface wave and scattered wave depths - sharp
  - Partial melt and lateral heterogeneity
- Continental lithosphere: moderate and extreme depth
  - Average or individual
  - Sharp discontinuity?
  - Influence of complex structures



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Magnetotellurics

- MT images electrical conductivity within the Earth based on telluric currents from natural sources.
- Conductivity depends on melt fraction, amongst other things.
- The lithosphere tends to be more resistive than the asthenosphere.
- Base of resistive continental lithosphere measured between 50 km and 400 km.
- Base of oceanic lithosphere is thin, up to 100 km
- Discrepancies between MT and seismic data up to 75 km

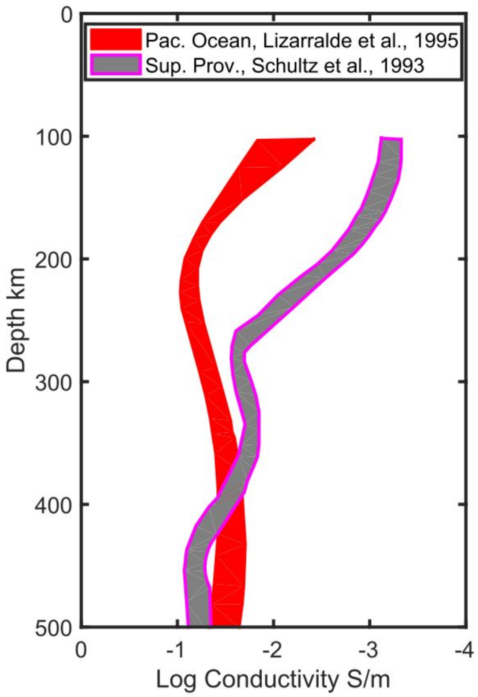
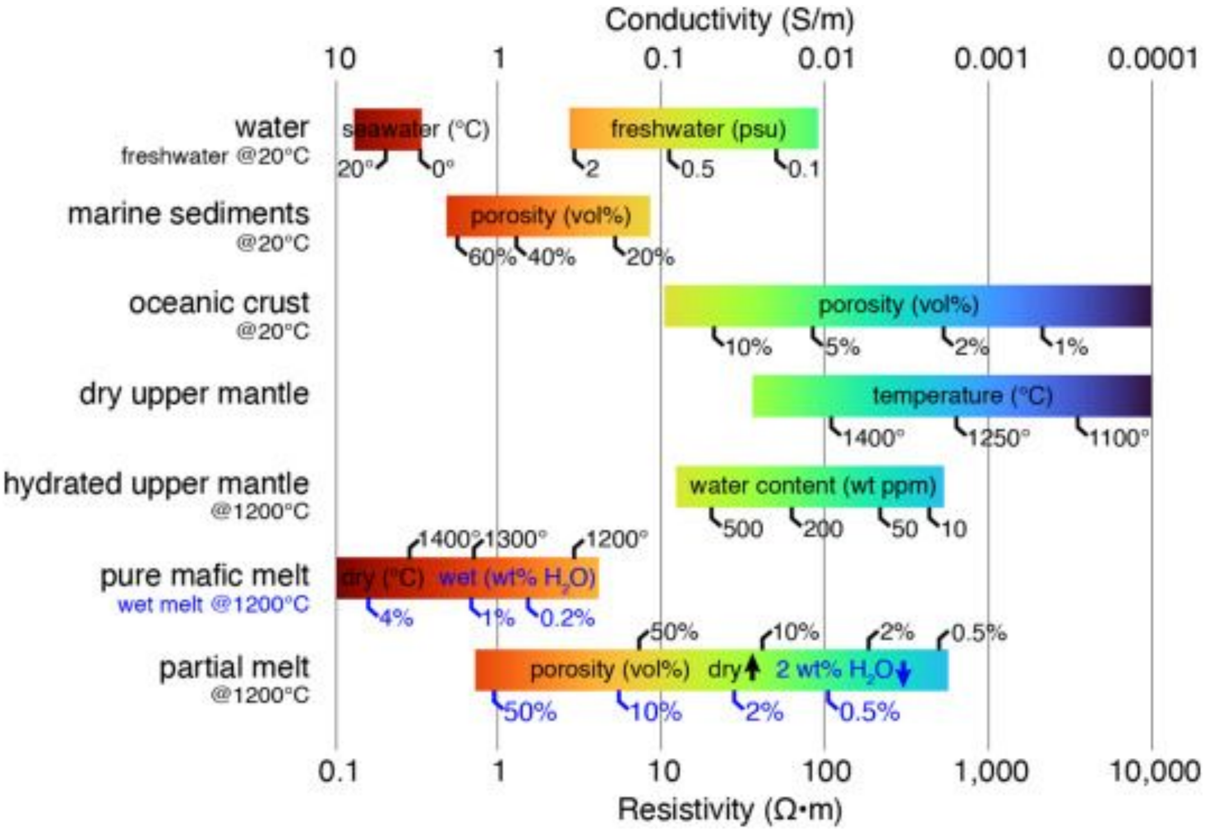
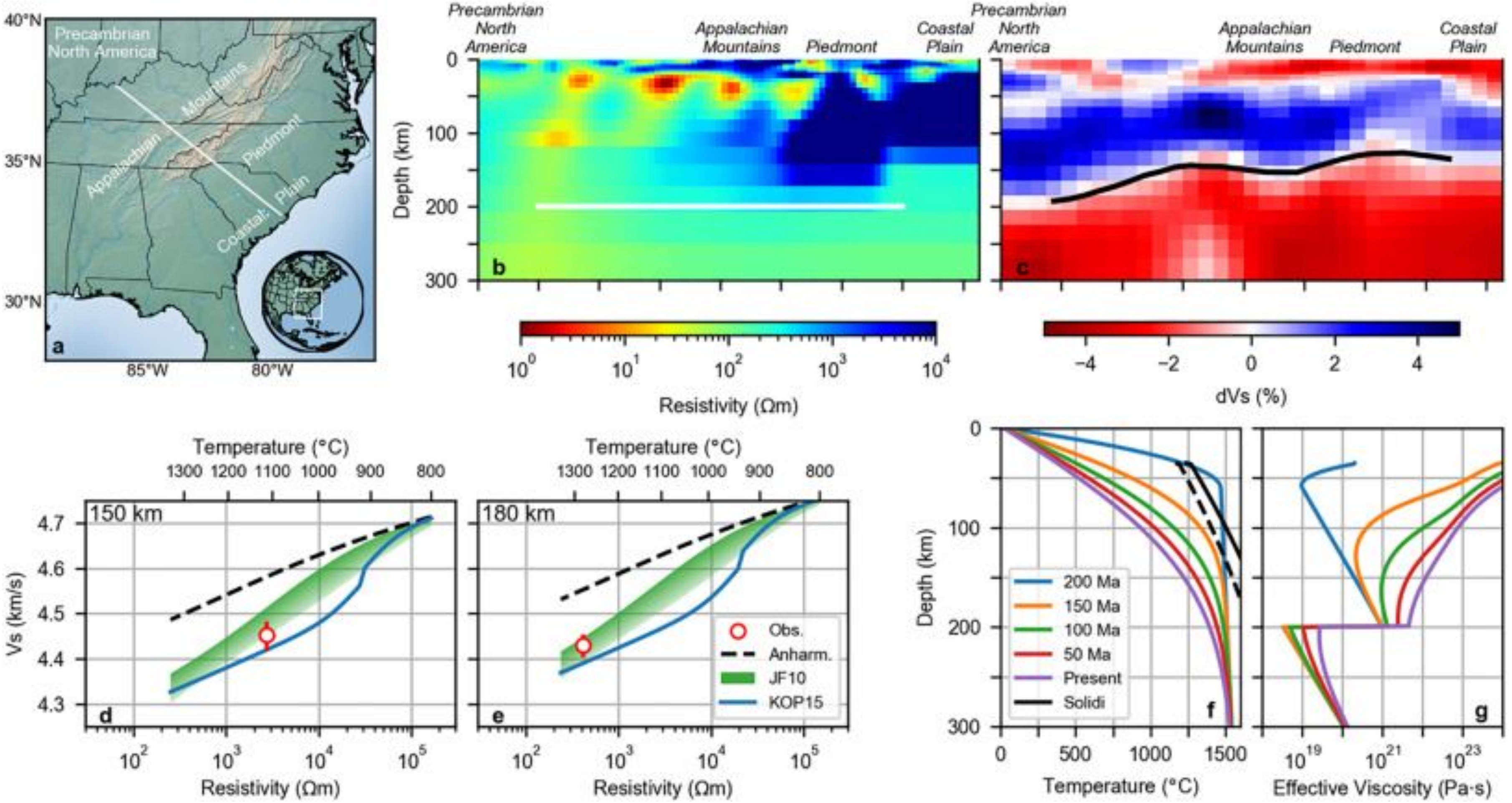


Figure 11. Electrical conductivity profile examples. The result from Superior Province is shown by the purple lines (Schultz et al., 1993), and the result from the Pacific Ocean is shown by the red line (Lizarralde et al., 1995).

Magnetotellurics





Naif et al. 2021

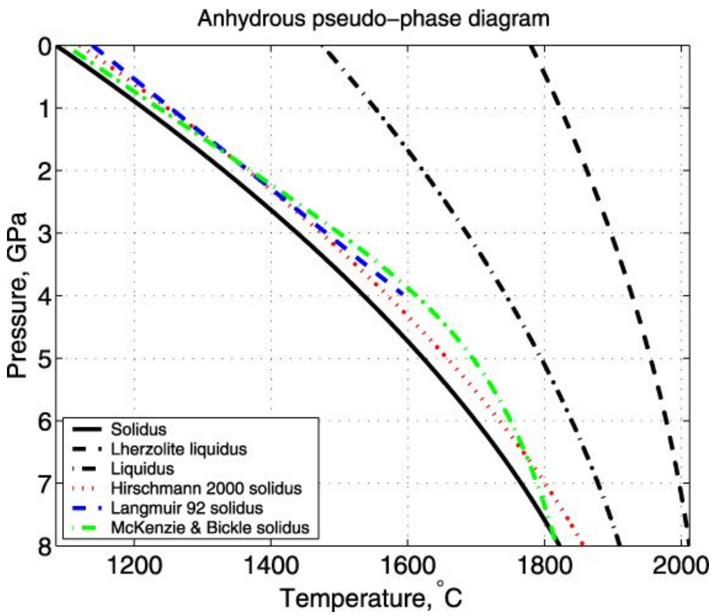
Asthenospheric melting

- Melting is dependent on temperature, pressure, composition, and volatile (particularly water) content.
- Katz et al. 2003 (and others) use these 4 parameters to develop melting models based on experimental data.

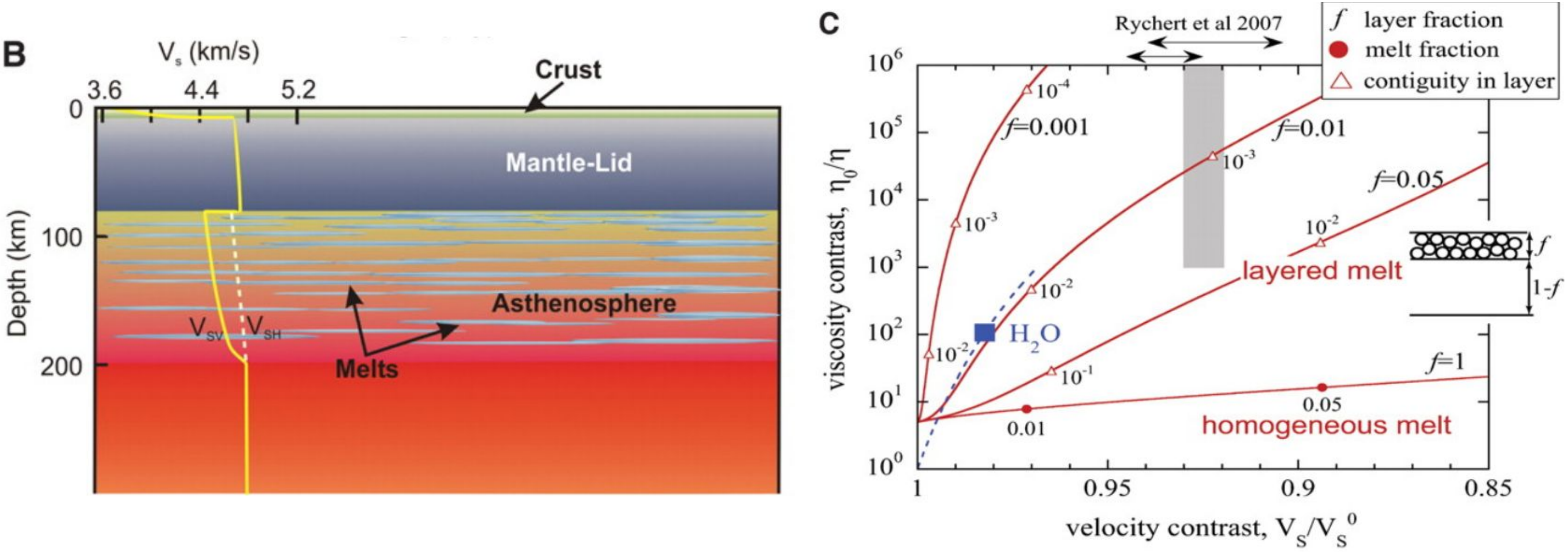
Since the temperature of the asthenosphere is typically below the solidus there are essentially two ways melting can occur:

- Pressure melting through upwelling
- Melting through the presence of volatiles (water)

Perhaps less than 1% partial melt fraction required to explain seismic LVZ and reduced viscosity in the asthenosphere.

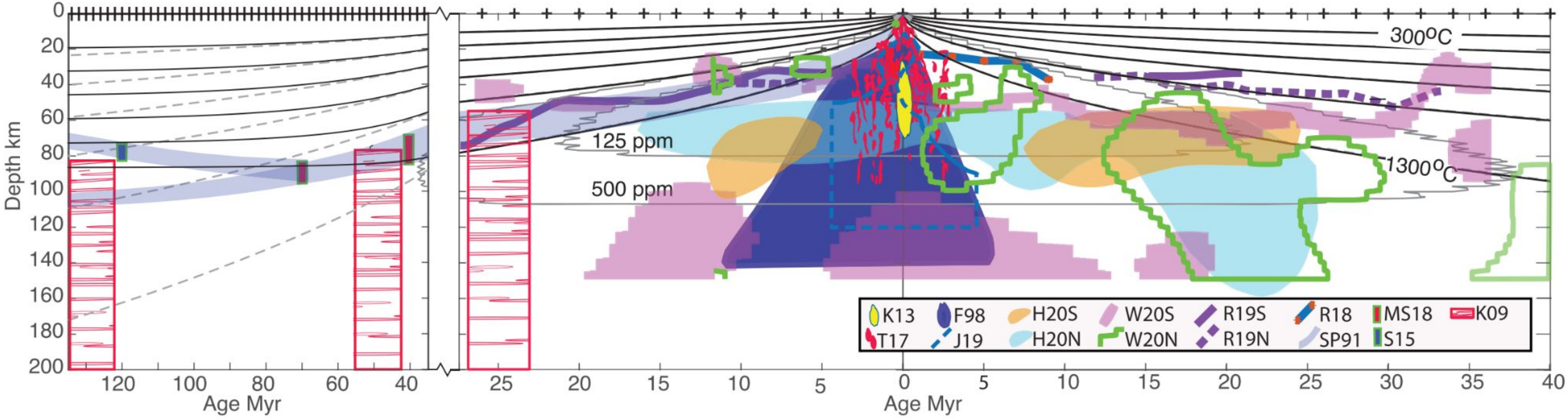


Melts in the asthenosphere below oceanic crust

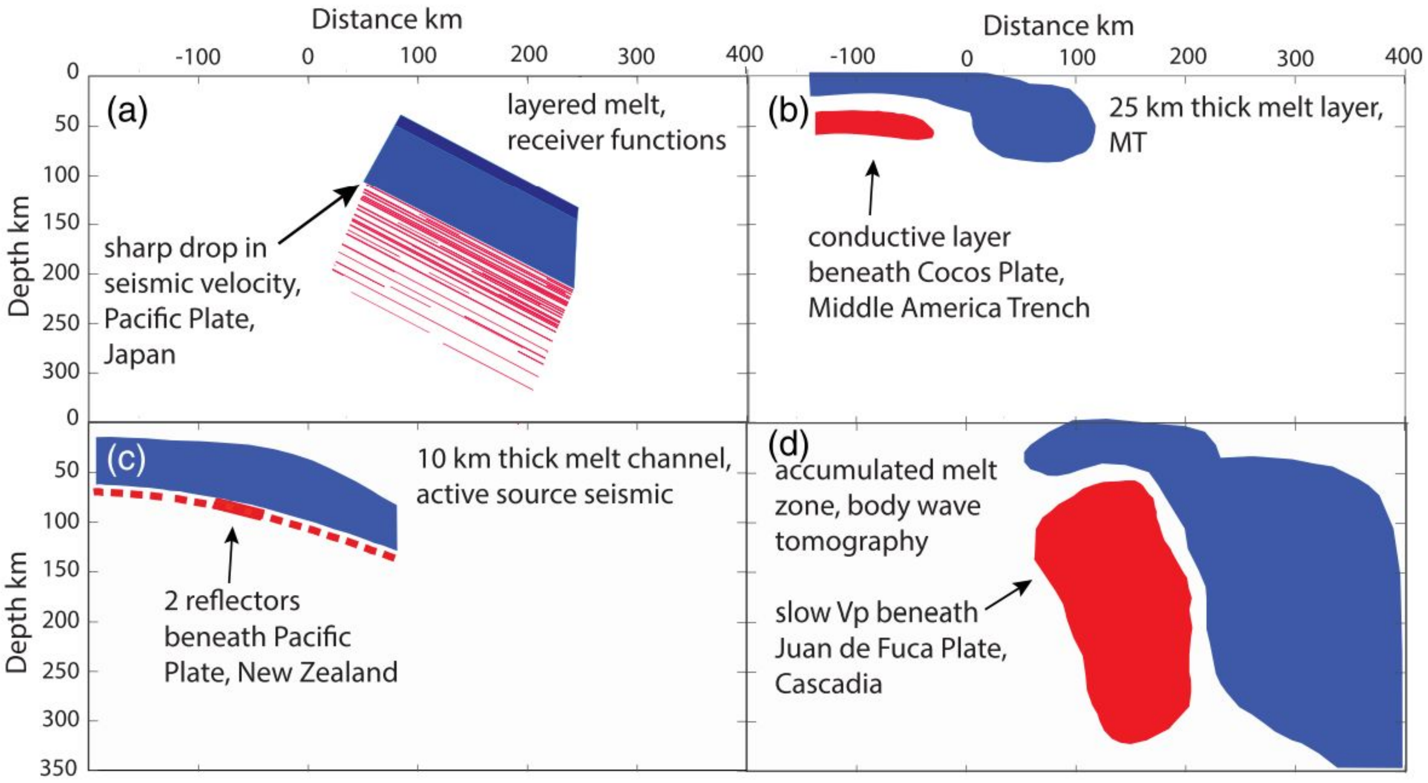


Kawakatsu et al. 2009

Prevalence of melt in the asthenosphere

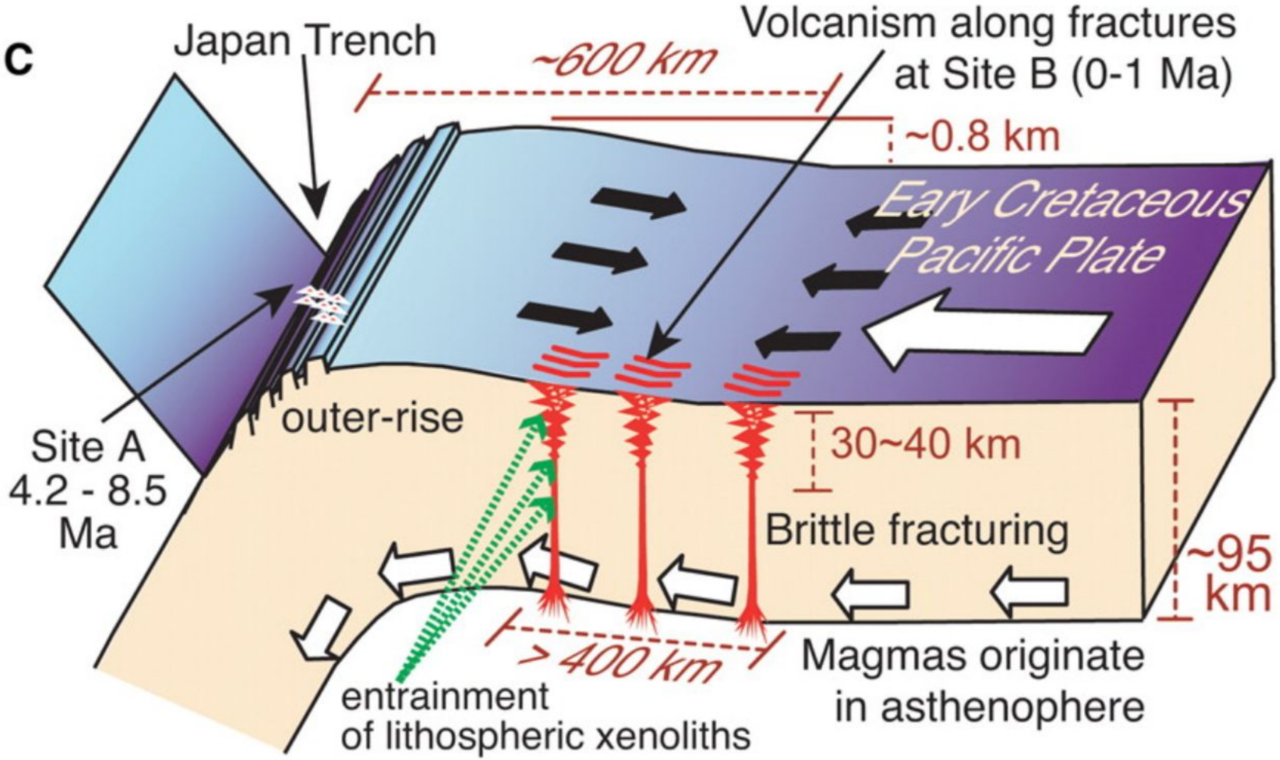


- The prevalence of melt near mid ocean ridges is strongly debated between authors.
- Partial melt likely to be responsible for low velocity zone (LVZ) in the asthenosphere.
- Presence of melt strongly decreases viscosity.
- Different models of melt migration can be used in numerical studies



- Some studies interpret the existence of regions of melt beneath subducted slabs as a result of upwellings. These regions may be layered in place, or ‘ponded’ below impermeable layers.
- Melt migration occurs much faster than geological time scales.

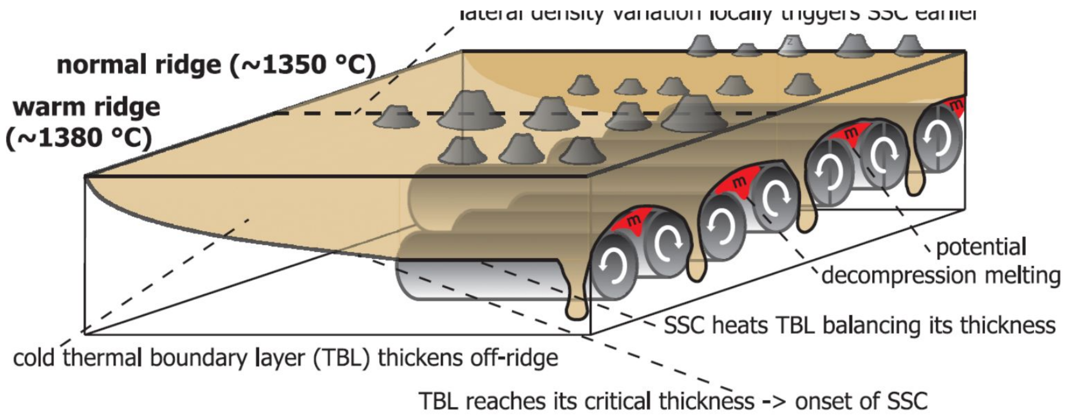
Petit spot volcanism

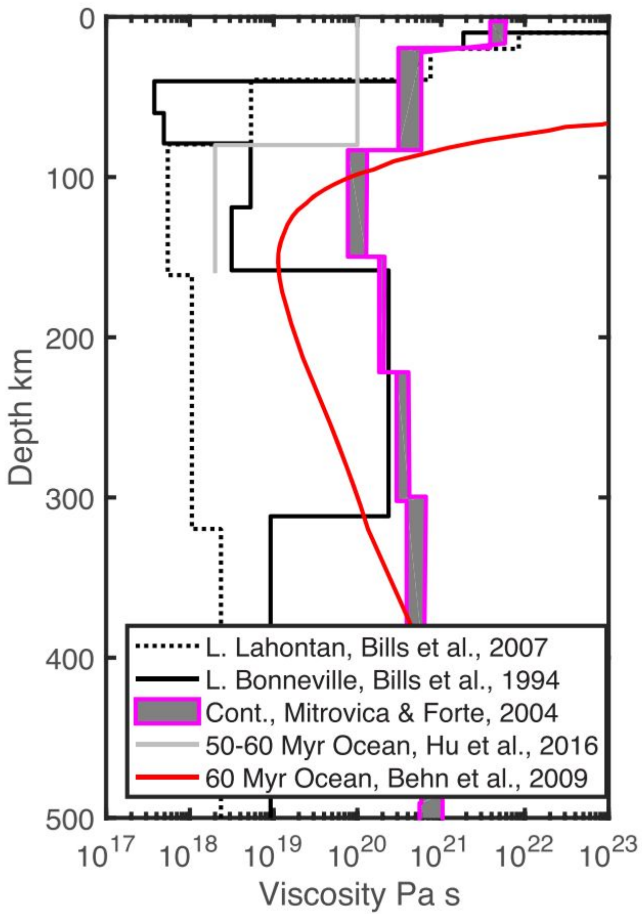


Hirano et al. 2006

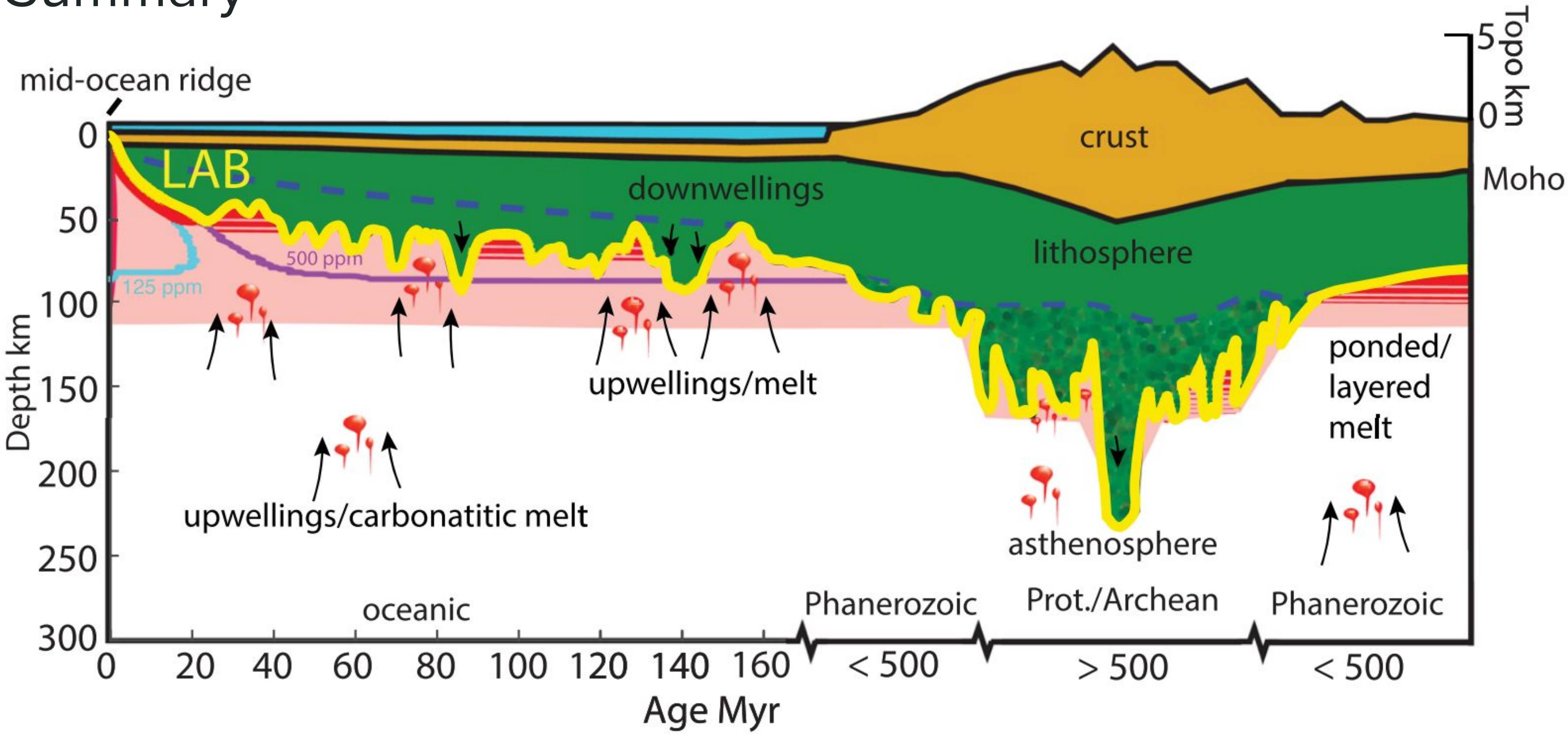
Geodynamic implications of the LAB

- Plate tectonics requires a relatively low viscosity asthenosphere to operate.
- Viscosity contrast across the LAB 2-3 orders of magnitude.
- Small scale convection is possible in a less viscous asthenosphere





Summary



mid-ocean ridge
LAB
crust
Topo km
5
0
Moho
downwellings
lithosphere
500 ppm
125 ppm
upwellings/melt
ponded/
layered
melt
upwellings/carbonatitic melt
asthenosphere
Depth km
0
50
100
150
200
250
300
oceanic
Phanerozoic
Prot./Archean
Phanerozoic
0
20
40
60
80
100
120
140
160
< 500
> 500
< 500
Age Myr

Summary

- Temperature contrasts alone are insufficient to explain complexity of LAB.
- Seismic data reveals a low velocity zone at LAB.
- Magnetotellurics demonstrates relatively high conductivity of the asthenosphere relative to the lithosphere.
- Prevailing theory is that partial melts are widespread in the asthenosphere, resulting in lower seismic wave velocities and decreased viscosity.
- Relatively low viscosity of the asthenosphere a key feature of modern day plate tectonics.